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Review of storage schemes for wind energy systems

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ABSTRACT

Wind Energy is a fast developing source of energy since 1996. Despite its advantages, this energy could never be a primary source of electric power to be integrated into the grid even in high wind areas, such as Great Plains, due to its intermittent behaviour. This intermittency will generate intermittent power to grid, which leads to instability, unreliability and power quality problem onto the grid system. One of the widely accepted methods to overcome this problem is by coupling the wind turbine with the energy storage system. This paper reviews the ability of four different types of the energy storage system to mitigate the power fluctuated into the grid, especially during low wind speed. This paper also explains the operating principles and the different methods of charging and discharging the energy storage. The ability of permanent magnet synchronous generator (PMSG) in dealing with variable wind speed also will be discussed.

Contents

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1. Introduction

By the end of 2003, the total integrated power by wind turbine has reached up to 39.234 GW and it is expected to increase up to 110 GW in 2012 [1]. Though wind energy is free, the cost in harvesting this energy is not cheap, albeit it is widely used in many parts of the world. The production of electricity using wind energy can save billions of barrels of oil and avoid emission of tons of carbon and other greenhouse gasses. For example, running 1 MW wind turbine for one year can reduce the following gasses from being released into the atmosphere [2]:

- 1500 t of carbon dioxide
- 6.5 t of sulphur oxides
- 3.2 t of nitrogen oxides
- 60 lb of mercury

Basically, wind energy is captured by generator blades before it is converted into mechanical energy, then into electrical energy [1]. The main drawback of wind energy is its non-uniform pattern because it varies by geographic location, time in the year and time of the day. It only operates when there is a wind flow. In fact, there is a minimum and a maximum speed for a wind turbine to start operating, which are called cut in and cut out. For most wind turbines, the 'cut in' speed is 4 m/s while the 'cut out' speed is 15 m/s. Wind turbines are usually recommended to operate at the speed of 7–10 m/s [2]. When the wind speed is more than cut-out wind speed, the system will be disengaged to protect the wind turbine system. So far, several command approaches have been introduced in dealing with these fluctuation problems such as adjusting pitch angle and rotation speed of wind power generator, transfering generated wind power through DC link and inverting control system and applying energy storage. Among these, energy storage is chosen as the most useful and effective method to handle this fluctuation problem because it consists of energy buffer that can effectively suppress even the fastest fluctuation. Energy storage with proper controlled system is able to absorb small variation in wind power output and reduces negative impact on the existing power grid [3,4].

Nevertheless, with the presence of energy storage, the surplus wind energy can be stored and be used at low wind speed or high peak demand. At the same time, it can also be used to mitigate the power fluctuation to be integrated to the grid during high wind speed. There are several publications that describe and review the ability of the energy storage system in grid application [5–8]. This paper describes the ability of four types of energy storage in smoothing the fluctuated power integrated to grid based on three categories, which are bulk energy storage, power quality, and distributed generation. These three categories have different performance in smoothing the fluctuated power based on their storage ability [9–11]. The storages are Compressed Air Energy Storage system (CAES), Superconducting Magnetic Energy Storage system (SMES), Flywheel Energy Storage System (FESS) and Hydrogen Energy Storage System (HESS). In order to create excellent mitigation in wind power fluctuation, an energy storage should have long life cycle to charge or discharge more frequently, high power density to endure power during charging and discharging process and high energy density to store abundant power. At the same time, the investment cost for an energy storage systems in possessing all the above characteristics can be reduced sufficiently [12].

Detailed description on grid problems caused by high saturation level of wind speed is illustrated in [13–15]. The problems that may occur are voltage and frequency regulation, power stabilization, reactive power control or voltage regulation capability, low voltage ride through, grid interconnections and control, system security, reliability and stability, load management and grid operation economics.

An integrated electrical power wind turbine integrated to grid cannot be delayed, but it can be stored to be used later. There are two problems regarding the integrated wind power without energy storage. The first is when the power demand exceeds the generated power during low wind speeds, and secondly is when the generated power exceeds the power demand during high wind speeds. The existing grid system has been operated for a long time without being connected to the energy storage. However, this system needs to go through over designing process to promise more energy generation capability and boosting production when the demand power exceeds the generated power. This problem normally occurs during low wind speed. Nonetheless, during high wind speed, the generated power would normally exceed the demand power, thus wind power needs to be discarded. With installed wind power capacity of 9 MW, roughly 27% of the available wind energy will be discarded. With energy storage, both problems can be solved by supplying stored energy when the power demand exceeds the generated power, and by storing the extra energy when the generated power exceeds the power demand. Despite being renewable energy source, the wind energy also encounters interruptions of electricity problem, just like the non-renewable energy sources have faced, like coal, natural gas and nuclear energy generation, such as shortage of fuel or malfunction of generating equipment [16,17].

There are three main types of generators that can be installed along with wind turbines; (i) squirrel cage induction generator for fixed speed, (ii) doubly fed induction generator for variable speed and (iii) permanent magnet synchronous generator for variable speed (PMSG) [18]. In [4,7,8], PMSG is suggested to be connected to variable speed wind turbine because of its higher efficiency, which leads to a better system performance. In addition, it also requires minimal maintenance cost and weighs less since it does not have external rotor current and gearbox, as in the system, gearbox is used to match turbine's low rotational speed (high torque) with generator's high speed (low torque) [19].

2. Energy storage operating scheme

2.1. Compressed air energy storage

CAES system is an electrochemical storage which is designed to store high pressure air during off peak and used during on peak. The first installation of CAES plant was at Huntorf plant located in North Germany in 1978. Time taken to fill the cavern was 8 h, and delivering 300 MW power was then achieved within less than 3 h. The cavern's volume was 310,000 m^3. Then, in 1990, a second and improved model of the first installation was built in Alabama, USA which had the storage capacity of 110 MW for 26 h. The cavern volume was about 538,000 m^3. However, this storage system had short time duration in running the compressor and

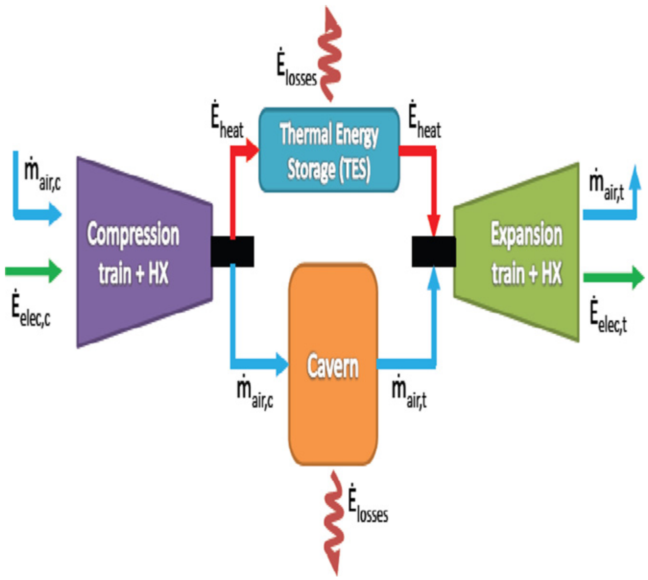

Fig. 1. Schematic diagram for CAES model [24].

expander. With no base load requirement, time taken to fill the cavern from 0% to 100% was less than 10 min. If a cavern was set to have a constant base load which is normally 10% of the full load, the time taken to fill the cavern would be almost 4 min; but could be shortened to 2 min when there was emergency [20]. Today, the number of CAES plants installed keeps on growing. The latest plant design incorporates adiabatic storage, which stores the thermal energy during the compression stage to be re-used during the expansion stage. Compressed air can be stored in salt cavern or hard rock [21]. The installation cost for CAES system is higher compared to the SMES, FESS and HESS systems. Despite of that, the maintenance cost for CAES system is the lowest compared to other three storages. The installation cost for CAES system is between $425/kW and $450/kW and the maintenance cost is around $3$10/kWh. The installation cost for the SMES system is approximately between $300/kW and $509/kW. FESS requires 350 $/kW for its installation cost and 18$/kW for maintenance, while $300$509/kW is required for the HESS installation cost and the maintenance cost is 3% of the capital cost [22,23].

There are three main stages in modelling adiabatic CAES, which are compression stage, air and thermal storage, and expansion stage, as shown in Fig. 1 [24,25]. This section will review the operation of these three stages in storing the energy to stabilize the grid system. One of the disadvantages of CAES is its reliance on geographical location. It is difficult to locate a suitable place to build a reservoir because some considerations have to be taken into account in terms of (i) location for a power plant can be constructed, (ii) distance to grid, (iii) size and structure are sufficient to run the compressor and expander [26].

Based on the above disadvantages, a novel method of utilizing constant pressure CAES combined with pump hydro storage is developed to reduce the storage volume size while maintaining the efficiency of CAES system [27]. An economic analysis was performed to determine the suitable location to place the CAES plant, whether close to the wind site or close to the load site [28].

2.1.1. Compression stage

In compression mode, the electricity from the grid is used to drive a motor to run the compression chain which forms a number of low and high pressure compressors and Heat Exchanger (HX). The number of compressor is equal to the number of HX. As the number of stages increased, power consumption decreases and storage efficiency increases due to the reduction of work done for each compressor to compress an air. Atmospheric air is compressed by the low pressure compressor, and then it goes into the heat exchanger to transfer part of its heat to Heat Transfer Fluid (HTF) in the heat exchanger. Next, the air goes into the next compressor and the process is repeated until it reaches the last compressor. Since salt cavern cannot store air with high temperature, this process will assist in reducing the air temperature every time the compressed air goes into the heat exchanger. If the area of heat exchanger is 0.83 m^2, the maximum temperature entering compressor (135 °F) can be reduced to (110 °F). Although the change in compressor seems linear during compression, the air pressure inside the cavern plays an important role in stopping the compression process. Compressor ratio, β_{ct} of the compressor train will limit the maximum acceptable pressure entering the cavern. Whenever the pressure inside the cavern reaches β_{ct}, the compressor will stop. β_{ct} value is normally varied between 45 and 70 bar based on cavern size. This compression ratio gives no effect on the expansion stage because the efficiency of expansion stage totally depends on the generated energy. The equation of a compressor ratio is shown as follows [20,24,29–32]:

$$\beta_{ct} = \frac{\text{Output pressure of compressor}}{\text{Input pressure of compressor}} \quad (1)$$

2.1.2. Air and thermal energy storage (TES)

There are two categories of air storage; also called as pressure vessel, which are underground storage and aboveground storage. Underground storage is normally used for large scale systems (100 kW and above) while aboveground storage is used for small scale systems (10 kW). Underground can be either of constant pressure type with variable volume, (e.g. aquifer or depleted gas reservoir), or constant volume type with variable pressure (e.g. salt cavern). The time taken for energy to be stored in aboveground storage is lesser compared to the underground storage [22,24]. In 2010, Marti et al. proposed a Maximum Power Point Tracking (MPPT) algorithm to obtain optimum energy conversion from the power fluctuation in tank [10]. Several parameters need to be considered in designing air storage, which are cavern depth, maximum input pressure, distance between caverns and size of the caverns. The cavern's pressure will increase as the depth increases. In order to avoid cracking around the cavern, the maximum pressure entering the cavern needs to be calculated to match with the cavern depth. The size of the cavern will determine the amount of energy stored and withdrawn from the cavern. In 2013, Proczka et al. [33] proves that storing compressed air in multiple caverns can increase storage's installation cost with only small reduction in storage length compared to single cavern. For large scale application of energy storage, salt cavern is chosen to store not only compressed air but also hydrogen gas or natural gas. This is because, salt cavern can provide very high withdrawal and injection rates which can help to meet high peak demand at short time duration, and has low cushion gas [34]. Salt cavern is formed by drilling conventional well to pump fresh water into a cavern. The salt dissolves, and the water is saturated. Then, water returns to the surface and the process repeats until a required volume and shape is obtained. In fact, the installation cost of the salt cavern is 60% lower than that of hard rock cavern. The efficiency of a cavern is based on the time taken to fill the cavern and to deliver power. The efficiency of the system is higher if the time taken to fill the cavern is shorter and the time taken to deliver the power is longer.

Thermal Energy Storage (TES) is used to store the thermal heat from a compressor to be re-used in the expander. Normally, this

storage is made cylindrically of high temperature concrete with height of 40 m, and radius of 11 m. There are two heat exchangers in TES, one that receives hot HTF from the compressor and the other that receives cold HTF from the expander. Here, the hot HTF during compression stage will be stored in TES to be used during expansion stage and the cold HTF temperature after the expansion stages is returned to TES to stabilize the system [20,24,35].

2.1.3. Expansion stage

This expansion stage is created by combining high pressure turbine (HPT) and low pressure turbine (LPT) with heat exchangers to re-heat the compressed air from the storage cavern. Basic operation of this stage is almost similar to gas turbine but it differs in input power to run the compressor. Two-third of the power generated from this stage is used to power the compressor in compression stage. This differs in CAES, where both stages are run with a separate motor and generator, thus power generated during expansion stage is fully integrated to grid system [36,37].

Since the compressed air temperature in the cavern is low, it needs to be raised at HX before entering the HPT. Once compressed air enters HPT, its pressure and temperature will drop. Then, air will pass through another HX to increase the temperature again before entering LPT. In LPT, the mechanical power is generated by expanding the air until it reaches the atmospheric pressure. This mechanical power will be used to run a generator rotor to convert mechanical power to electrical power. Generated power will be fed to the grid through a high performance power conversion system (PCS). PCS is formed using back-to-back AC/DC/AC converter and used to control the exchange of the active and reactive power flows. Power rating of this generator is inversely affected by the rotor speed that functions to move the generator. As the rotor speed increases, the power rating of the generator will be decreased. The electric power produced can be used to smooth up the power fluctuated at the applied load. The hybrid interconnection between wind turbine and CAES is illustrated as in Fig. 2.

The input pressure of the expander needs to be considered to obtain high air pressure, high speed of turbine and high value of DC output voltage after expansion stage. These values will not be reached if insufficient pressure enters the expander. From the simulation result in [24], higher input pressure will increase turbine speed and shorten the time taken to empty the tank during the expansion stage, where the DC voltage can be obtained.

The heat loss during expansion stage is lower compared to compression stage because the air mass flow in the compressor (120 kg/s) is one-half than the air mass flow in the expander (240 kg/s). Thus, small energy loss will occur during the 11 h of expansion compared to the 23 h of compression. Hence, even until the last one cools down at expansion stage, the wall still receives heat from the air. Generally, the value for air mass flow rate in both stages is given and constant along both stages [24,31,38].

2.2. Superconducting magnetic energy storage

Superconducting magnetic energy storage (SMES) is an energy storage which stores energy in the form of magnetic field created by flow of direct current in a superconducting coil. This coil is immersed in liquid helium, and its temperature is cryogenically cooled to a temperature below the superconducting critical temperature. This operation is applicable to improve the power quality for critical loads, providing carryover energy during voltage sags and momentary power outages in SMES system. The earliest SMES installation was in United States with the capacity of 30 MJ. This installation was tested by Bonneville Power to provide a controlled system and frequency regulation on long transmission lines along the west coast. Other installations with various capacity of SMES can be found in Japan, which function to measure the stability of the distribution line, a 5 MJ SMES at Hitachi Works and 1 MJ with Chubu Electric [39,40].

SMES system can charge or discharge power in short time duration even with small storage size. SMES system does not only have a quick respond to absorb or dump active power but also can provide reactive power, thus it is able to mitigate the voltage fluctuation based on the load change in a grid system. The capability of SMES system to mitigate the wind fluctuation is acknowledged in [41] due to its long life cycle, high power and energy density. Nonetheless, SMES system is normally operated only under several kV to avoid coil destruction during the voltage breakdown. This storage system consists of superconducting coil, cryogenic system, and a power conditioning system. One of the disadvantages of SMES system is its small size due to high installation cost and short-live energy content. There are three stages in charging and discharging the superconducting coil, which are superconducting coil, cooling system and power conditioning system [42,43].

In 2011, Ngamroo [44] performed a study to design an optimized robust SMES controller by considering the superconducting magnetic coil size and system uncertainties. Molina explains that SMES can also be applied on high-power utility system by constructing a critical analysis on power conditioning system of SMES to control both active and reactive power flows in the transmission network level [45].

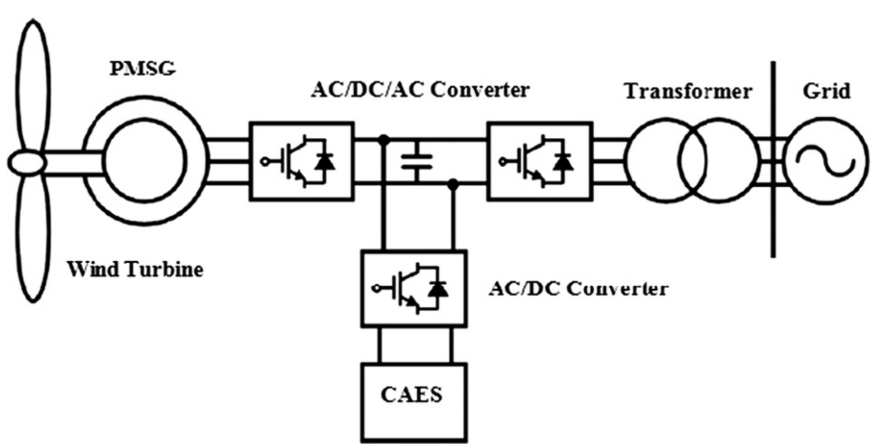

Fig. 2. Schematic diagram of CAES and wind turbine model [25].

2.2.1. Superconducting coil

Coil is the main part of an SMES system where it can absorb and release power based on power demand. There are two types of coil normally used in SMES which are toroid coil and solenoid coil. Particularly, toroid coil is applied in small and medium scale storage while solenoid is applicable in large-scale storage. The coil is connected to PCS through vapor-cooled leads (VCL). Fig. 4 shows a control system which controls the current flow from and to the DC link. Coil will start charging every time the output power of rectifier exceeds the reference power, and the coil will discharge when the rectifier output power is less than the reference power. The amount of SMES current required to charge and discharge the coil is inversely proportional to voltage across the coil during discharging. This is illustrated in Eq. (2) below. I_S is the critical current and P_o is the constant generated power when the DC current reaches critical current. The SMES current will be discharged until it reaches a critical value. Then, the system will no longer discharge and the generated power is at steady state response. The amount of energy stored in SMES coil, E_{SMES} is directly proportional with DC current flow to the coil, as given in Eq. (3). L is the inductance of SMES coil [2,46,47].

A few assumptions had been considered in modelling the SMES system: (i) superconducting coil had to have a large inductance, so the ripple effect of the direct current would be ignored, (ii) zero coil resistance, (iii) ignoring the voltage drop in the converter and (iv) neglecting the harmonic power generated inside the converter [48].

$$I_s = \frac{P_o}{V} \tag{2}$$

$$E_{SMES} = L\frac{I_{SMES}^2}{2} \tag{3}$$

2.2.2. Cooling system

As the surplus DC current flows through the superconducting coil, the coil temperature will increase, but this temperature can be reduced by using thermal shield or liquid helium. An operating system which is called cryogenic system, functions to maintain the required temperature to enhance the performance of superconducting operation.

A thermal shield will be used to cool down the coil temperature when the coil is forced to cool down; however, during the pool boiling, liquid helium will be used to cool the coil. Instead of thermal shield, liquid helium is more popular in cooling down the superconducting coil due to its better performance in term of AC loss and overvoltage [49,50].

2.2.3. Power conditioning system

PCS is composed of 12 pulse cascaded bridges of AC/DC converter or DC/AC converter. This inverter will produce energy losses in each direction, but these losses can be reduced by connecting the SMES system directly to the DC link because of the stored energy in DC. Thus, by controlling the DC/DC converter, the stored energy can directly be transferred to the grid system through DC/AC grid side converter as shown in Fig. 3 [51].

The controlled DC/DC converter is based on two output quantities of a typical SMES (voltage and current), modulation index and phase angle of the converter. The phase angle is used to tune the active and reactive power of generated SMES [52].

2.3. Flywheel energy storage system

Flywheel energy storage system (FESS), is a mechanical energy storage that stores energy in the form of kinetic energy in rotating mass. It has been used for many years to store energy and to stabilize variable speed operation of rotating machine. The first generation of FESS was composed of a large steel wheel that was attached to an axle to produce mechanical power. This kind of FESS could only be applied in small scale energy storage because the energy generated from FESS was inversely proportional to the size of flywheel. Thus, in 1970, this model had been upgraded by using carbon-fiber composite rotors which had more tensile strength and less heavy. In fact, with the help of modern electronics, this new generation of FESS gives more efficient voltage and frequency control of output power despite its rotational speed of flywheel. Higher frequency may contribute to hysteresis loss in the stator core that can increase standby losses.

A FESS is composed of rotor, motor/generator, bearing system, vacuum housing, and power electronics converter. Rotor is the main part of FESS, which functions to limit the stored energy. There are three operating modes that will be described in this part, which are charge mode, stand-by mode and discharge mode [39,40,53].

In term of wind fluctuation cases, FESS has the advantage in coping with this fluctuation because it has long life cycle, high power and energy density [54]. Despite that, the disadvantage of FESS is the electromagnetic force of magnetic source (usually permanent magnet) which depends on the field strength. As the magnetic sources are reduced, stored energy would also be reduced. To overcome this problem, a study was constructed to compare the ability of permanent magnet and superconducting coil to improve magnetic field source [55]. In 2012, Tang and Ge performed another analysis to improve the rotor stability and reduce the radial amplitude of rotor vibration in [56].

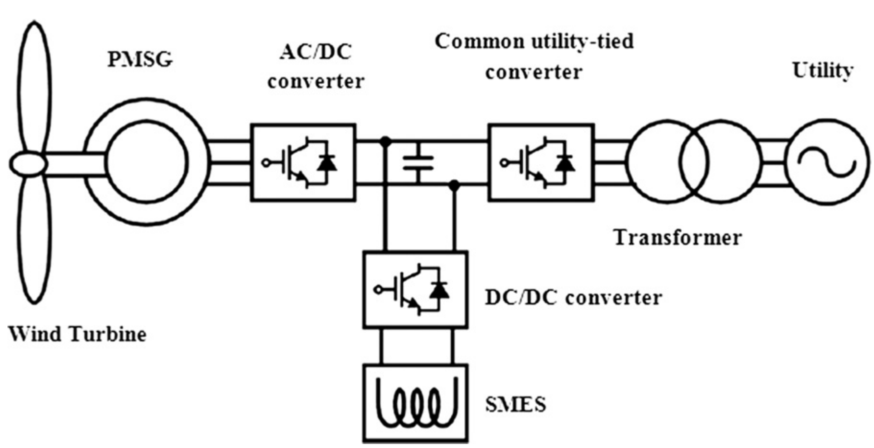

Fig. 3. Schematic diagram of SMES and wind turbine model [51].

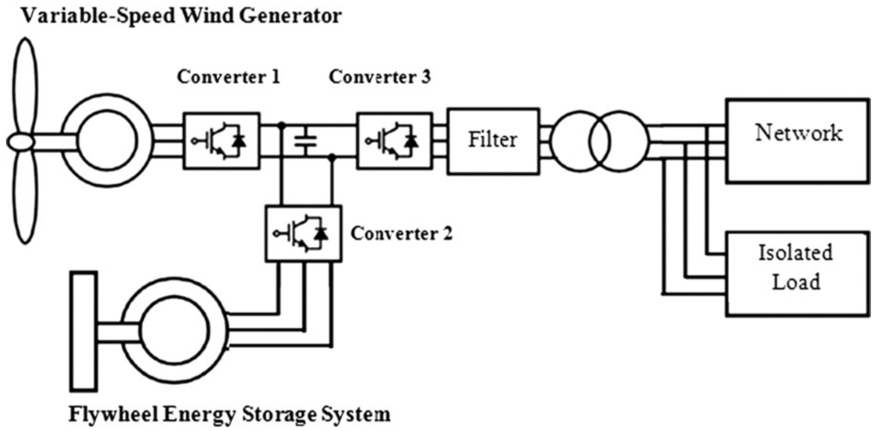

Fig. 4. Schematic diagram of FESS and wind turbine model [58].

2.3.1. Charge mode

Based on Fig. 4, during charge mode, converter 3 will run as a rectifier while converter 2 runs as an inverter. In converting kinetic energy to electrical energy, the electrical machine works as a motor that absorbs the electrical energy accelerating the shaft. Rotor is used to accelerate the shaft until it reaches sufficient working speed and this speed is maintained by using small additional input energy [39,57,58].

There are two types of material used in constructing a rotor which are composite material such as carbon-fiber, and steel. The first material has a high strength to weight range, which can accelerate the rotor speed up to 100,000 rpm. The second material produces large diameter, slow rotation and low power density, which can slower the rotor speed up to 10,000 rpm. Kinetic energy, E stored inside the rotating mass is given as

$$E = \frac{1}{2} I w^2 \tag{4}$$

where I is the moment of inertia of the flywheel and w is the angular velocity. From Eq. (3), it shows that the energy storage inside the rotating mass is directly proportional to the angular velocity of the rotor, thus to increase the energy storage inside the rotating mass, the rotor should be made to spin faster. However, the diameter of FESS has nothing to do with rotor speed. A large diameter can have the same energy level with a small diameter that rotates faster [24,40,59].

In modelling the FESS, commonly two parameters are tested: (i) ironless stator is used to minimize stand-by losses, and (ii) a stator cable is placed in between neodymium–iron–boron magnet and ferromagnetic steel rim to achieve high power density in a generator with ironless stator [53].

2.3.2. Stand-by mode

Once the working speed is reached, the shaft will be disconnected but this shaft will keep on rotating because of the inertia of the flywheel. This rotation shows that the electrical energy is fully converted into kinetic energy, and the energy is stored in rotating mass. In this manner, the storage system is ready to discharge. To increase the efficiency of the shaft, bearing friction, aerodynamic losses and other mechanical losses must be eliminated. For example, by placing FESS inside vacuum containment, the friction-loss from air can be eliminated and suspended by bearings. The weakness of FESS is its high standby loss, which is only within 5% of power rating [53,57].

2.3.3. Discharge mode

To discharge the energy storage inside the rotating mass, the moving shaft will produce torque to run the electric machine which works as a generator to produce electricity. In this mode, converter 2 will act as a rectifier and converter 3 acts as an inverter. This energy can be discharged continuously without being interfered because the energy is stored mechanically and not chemically. As the flywheel discharges, the flywheel's rotor speed gets slower and the stored energy decreases. The schematic diagrams of FESS and wind turbine are illustrated as in Fig. 4 [40,53,57,58].

2.4. Hydrogen energy storage system

Hydrogen Energy Storage System (HESS) acts as an energy carrier for stochastic energy sources for long duration. Hydrogen can mostly be found in the combination of natural gas (CH_4) and H_2O. About 90% of hydrogen is extracted from natural sources such as natural gas, coal and oil through reformation process. Today, hydrogen can be extracted using electrolyzer, which allows operating using renewable energy and nuclear source, called as electrolysis process. The process is started by converting electricity into hydrogen using the electrolysis process, and then stored in a hydrogen storage tank, then finally converted back into electricity during peak hours or during low wind speed. In an electrolysis process, when the electric current generated from wind turbine and passes through the water, the hydrogen atoms of the water (H_2O) approach the positive electrode (anode), and its oxygen atoms approach the negative electrode (cathode). This can be expressed by chemical equation as follows:

$$H_2O = H_2 + \tfrac{1}{2}O_2 \tag{5}$$

Faraday's law for electrolysis states that, 'mass of substance produced at an electrode is proportional to electricity transferred at that electrode'. By varying the operating power of electrolyzer, more H_2 can be produced. There are three steps considered in charging and discharging the energy storage which are hydrogen generator, hydrogen storage and discharging mode [39,60,61].

HESS has low capability in smoothing wind fluctuation due to its short life cycle and low power and energy density. These characteristics give low performance in converting electricity to hydrogen and vice versa [62,63]. Four precaution steps as listed below need to be considered when combining HESS with wind turbine to promise a better performance of HESS [64–67]:

(i) Maintaining the current and voltage at rated value.
(ii) Flexibility to operate above minimum current whenever possible to avoid current increasing as the gas produced increases.

(iii) Not interrupting the electrolyzer once it is on. Need to maintain a minimum standby current to protect electrodes from corrosion.
(iv) Avoiding fast variations response of the electrolyzer.

2.4.1. Hydrogen generator

Hydrogen generator is composed of rectifier, DC chopper and an electrolyzer. This generator will operate when some parts of wind farm output are rectified, then the DC chopper supplies DC current to electrolyzer to produce hydrogen gas. A controller is needed to maintain DC current at a rated value to ensure that constant hydrogen is produced. Error signals between hydrogen generators consume real power that will be the input to the gate of DC chopper along with reference power. Electrolyzer cell consists of an electromotive force and internal resistance as illustrated in Fig. 5. At rated operation, the electrolyzer generates rated power of 44.075 kW. Power generated from electrolyzer is shown as follows [39]:

$$P = VI$$
$$P = 107.5 \times 410 = 44.075\ \text{kW} \quad (6)$$

2.4.2. Hydrogen storage

Hydrogen can be stored in many ways. One of the ways to store hydrogen is by storing the hydrogen gas generated inside the wind tower itself. However, some considerations have to be made in designing this type of tower because hydrogen tends to react with steel. Hydrogen can also be stored as compressed gas, as cryogenic liquid, in solids (metal hybrids, carbon materials) and in liquid H_2 carriers (methanol, ammonia) [60]. Besides that, for large HESS application, salt cavern (as mentioned in Section 2.1.2) can be used to store hydrogen [68].

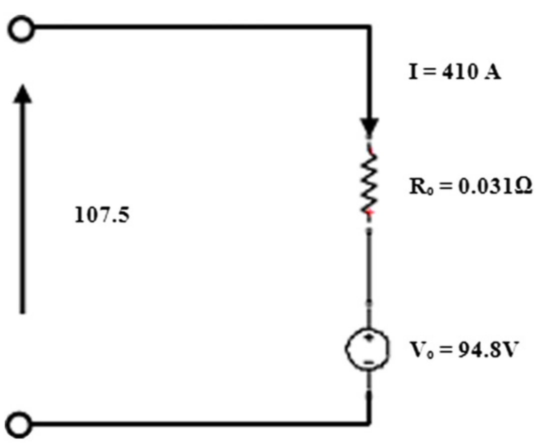

Fig. 5. Equivalent circuit of electrolyzer cell [39].

Stored hydrogen in the form of compressed gas can be distributed in dedicated pipelines over a long distance, while the liquid stored hydrogen can be transported in tankers by rail, ship or road to the urban area. Unlike other mentioned energy storages above, the hydrogen energy can be produced close to the point of use [69].

2.4.3. Discharging mode

HESS will normally be connected along with stochastic sources to prevent the extensive upgrade of the existing grid system in view of future load growth and low wind speed. The HESS will discharge when the stochastic generation surpasses the local load and whenever a load is higher than import capacity, where the stored energy will be used. Besides that, HESS can also be connected to the H_2-fuelled vehicles or H_2-pipeline network for further distribution. H_2 fuelled vehicles can be used to feed large vehicles like local ferry and bus. It is potentially worth to build a HESS with filling station around this kind of area [17,70].

3. PMSG with variable speed wind turbine

There are two types of wind speed considered in defining a wind turbine, which are fixed speed and variable speed. Fixed speed wind turbine is normally coupled with squirrel cage induction generator (SCIG) while the variable speed wind turbine (VSWT) is normally coupled with double feed induction generator (DFIG), wound field synchronous generator (WFSG) and permanent magnet synchronous generator (PMSG). As the wind energy fluctuates, VSWT ensures optimum power compared to fixed speed because it can produce optimum power at high wind speed. Strengths and weaknesses of fixed speed/constant speed wind turbine and variable speed wind turbine are simplified, shown in Table 1. Doubly fed and direct drive in this table illustrate the VSWT while the constant speed is explained as SCIG [71].

VSWT with PMSG is chosen to be discussed further in this paper because it gives a better performance of power integrated wind turbine due to higher efficiency and less maintenance. Besides that, PMSG can be designed with higher number of poles which leads to a gearless low speed. Variable wind speed is able to optimize the performance of the power integrated from the wind turbine, reducing mechanical loading and delivering or absorbing active power plant control. VSWT uses power electronic converters to allow real time rotational frequency to couple with a grid frequency to absorb wind speed fluctuations. It allows the rotor to accelerate or decelerate, thus smoothing out spikes in power, torque and voltage.

Table 1
Brief comparison on advantages and weakness of fixed speed and variable speed wind turbine [71].

	Constant speed	Doubly fed	Direct drive
Strengths	Simple and robust Less expensive Electrically efficient Standard generator	Less mechanical stress Less noisy Aerodynamically efficient Standard generator Small converter suffices	Less mechanical stress Less noisy Aerodynamically efficient No gearbox
Weakness	Aerodynamically less efficient Gearbox is included Mechanical stress Noisy	Electrically less efficient Gearbox included Expensive	Electrically less efficient Large converter necessary Expensive Heavy and large generator Complex generator

Running variable speed wind turbine with PMSG can produce optimum integrated power to grid because of its higher energy gain and the reduced stress. In PMSG, the excitation voltage is provided by the permanent magnet itself, so no external field windings are required. Due to the large air gap, PMSG is able to reduce flux linkage in machines, thus leading to the formation of a small size low rotational speed generators. The size of the generator is based on the power ratings. In fact, no gearbox is required because of the low rotational speed in PMSG wind generator, and the installation cost can be reduced and the circuit can be more simplified [26,72–74].

For the duration of variable wind speed, PMSG has two control goals; first is to maintain maximum power coefficient by keeping constant maximum tip speed ratio during low wind speed. Second is to achieve rated power output during high wind speed by increasing the value of pitch angle. Increasing the pitch angle will also increase the rotor speed and tip speed ratio. Therefore, the power coefficient will decrease to keep the output power at rated value. As the generator speed increases, electrical power and torque are also increased until it reaches a steady state value but the changes in torque would be slightly lower than the power [72].

Each variable wind speed has its own maximum power point and it is traced using MPPT. To operate wind energy conversion system at maximum power point and at high efficiency, the rotating speed of wind turbine needs to be adjusted to capture maximum wind power. A conventional MPPT faces many problems due to wind speed fluctuations and generator's heavy inertia, so a new variable step MPPT has been developed. A suitable MPPT control scheme to be connected to the PMSG is developed to produce 350 V direct current voltage to the DC link. The differences between variable step MPPT and conventional MPPT are as follow:

(a) Variable tracking step of MPPT control based on the change of wind speed.
(b) Avoiding dead time effect of the inverter, MPPT synchronizes the rotating speed of the generator.
(c) Low pass filter at the output of the MPPT is used to reduce the fluctuation of rotating speed reference.

A fixed speed step can cause rotating speed fluctuation and slows the tracking for fast variation of wind speed. The inverter dead time causes ripple in torque current and consequently affects the power comparing in MPPT algorithm. Fluctuation of rotating speed causes unstable wind turbine. This issue is analysed in [75] and a adaptive filter with a Fuzzy logic based MPPT controller is proposed. The results obtained show that the proposed 'generic' MPPT controller gives better performance in tracking wind velocity compared to the wind sensor method. Another publication in improving the performance of MPPT proposed a variable step MPPT method [74] to trace the maximum power point of wind velocity. This method proves that the wind velocity can be traced as fast as 0.2 Hz (within 5 s) and it is stable. It is also able to increase the output power as much as 48% compared to conventional MPPT control method [76,77].

4. The effects of energy storage on grid system

Wind energy promises a clean and non-polluting energy source and is the fastest growing trend which will play a very important role in the near future. Unfortunately, the main drawback of wind energy is its strong dependence on weather. Sudden change in wind speed causes large fluctuations in the wind output power. This power fluctuation leads to several challenges and issues. In order to endorse large scale wind energy to be integrated to existing grid, these power fluctuations need to be smoothened out.

The challenges that are incorporated with wind energy integrated to grid are as follow; wind intermittency, frequency deviation, fault ride through capability of wind turbine and ramping due to wind speed variation. Combining an energy storage system with wind turbine through suitable power conversion can minimize some of these challenges. Since energy storage system has both real and reactive power control abilities, it can act as a "shock absorber" to improve the efficiency, stability, and security of the power system. Without energy storage, the industry needs to maintain the entire delivery network during peak demand but with energy storage, the industry only needs to build what is required to carry normal load [71,78]. Four types of energy storage as mentioned before, will be explained in this section.

4.1. Compressed air energy storage

CAES system is a bulk energy storage that stores compressed air during off peaks and uses it during on peaks. Simulation results in [25] show that the generated power from CAES system is able to smoothen the power fluctuated during variable wind speed and also able to maintain the power integrated at grid level during low wind speed. In [10,16,79,80], the power generated from CAES is reduced as the time taken for CAES to supply to the load is increased. As time increases, air mass and pressure inside cavern will decrease which leads to small amount of compressed air to be expanded by the expander of CAES. In [50,81], it shows that the power generated from CAES when running the compressor only at early morning and at night is smaller compared to when running the compressor at any time. This is because the stored energy that is used to supply to the grid during the day time can be stored at the same time by purchasing small energy from grid to run a compressor. Surplus energy during high wind speed is stored in the cavern and this energy will only be used when the pressure inside cavern is more than 13 bar, which is a minimum pressure inside the cavern.

In 2012, Latha, Palanivel, and Kanakaraj explained the latest application of CAES in improving grid performance in term of frequency regulation in [82]. This paper proposes an air flow controller to control the air flow from CAES system, to ensure microgrid follow the various load demands which can maintain the stable grid frequency.

4.2. Superconducting magnetic energy storage

In [50,83], it shows that the surplus DC current generated during high wind speed will be absorbed by SMES in order to maintain constant DC voltage. Once the current is absorbed, the current will not decay thus magnetic energy is stored. At low wind speed, the DC current from SMES will be released back to the network through a DC–DC converter. A main drawback of SMES is its high cost of its superconducting wire, which will shorten the time duration of energy storage to store energy.

Based on the simulation results in [40,84], SMES not only can mitigate power fluctuation but also can stabilize the grid system when fault occurs. Besides that, when a 2.5 MJ SMES system is connected to the grid during day time, the output active power of wind generator and system frequency is more stable compared to when 1 MJ SMES is connected, because the system frequency fluctuation level depends on the SMES capacity. In other words, the higher the SMES capacity, the more stable the system frequency will be.

In 2012, Jin and Chen also presents the latest invention of SMES in its application with smart grid using hybrid SMES and distributed SMES. For hybrid system, the SMES is combined with battery energy storage or super capacitors. In distributed SMES, small scale SMES is distributed in different locations and to

Table 2
Brief comparison on four types of energy storage [22,23,37,84].

	Application category	Discharge power range	Discharge time	Discharge efficiency	Stored energy range	Life cycle (years)
CAES	Bulk energy storage	10–1000 MW	1–8 h	0.79	10-8000 MWh	> 40
SMES	Power quality	0.1–2 MW	1–30 s	0.95	0.1–60 MJ	> 20
FESS	Power quality	0.1–2 MW	1–30 s	0.93	0.1–60 MJ	> 10
HESS	Distributed generation	100–200 kW	0–504 h	0.59	50–8000 kWh	20

ensure all the SMES unit work harmoniously by controlling each SMES. To improve grid infrastructure, FACTS and DFACTS are tagged along with both systems to enhance the power quality. Analysis results show that the power generation, transmission, distribution and consumer side, the hybrid SMES and distributed SMES have promising prospects in future smart grids [85].

4.3. Flywheel energy storage system

Flywheel is also an energy storage designed to deal with short-voltage disturbance in order to improve power quality occurrence. In order to prevent the flywheel speed from reaching its saturation limits, by depending on flywheel capacity and by setting closed loop specification of power controller in the form of disturbance rejection, the power delivered to the grid is varied but made smoother compared to standalone wind generated power. These are all because of dominant dynamic between the torque at the turbine's blades and generated power of the drive train, which can sufficiently reduce the disturbance when the cut-off frequency response of the drive trains. In fact, FESS has the ability to maintain the voltage across distribution network up until 98–102% of rated value and able to supply 10 kW active power in 15 min. To maximize the generated output power of FESS to grid system, eddy current losses have to be kept at minimum by preventing the interconnection between the stator and magnets [53,86].

The experimental result in [58] shows that FESS is able to improve the quality of generated active power to grid. The intermittent nature of wind energy causes large power fluctuations integrated into the grid system, but with the presence of FESS, this fluctuation can be minimized. Larger flywheel inertia gives better power levelling. Besides that, by controlling the FESS suing the PI voltage controller, the DC link voltage can be kept constant at rate. This is because, every single power generated from FESS will be compared with expected power generated to grid. This comparison can determine how much power is required to maintain constant DC voltage.

4.4. Hydrogen energy storage system

With the presence of HESS in combination with wind turbine, it can reduce the dumped generated wind power especially at high wind speed. The reduction can be up to 27% of generated wind power. It also shows that, more H_2 can be produced when varying the operating power of electrolyzer. In addition, it can reduce the grid losses and can promise high power prices for import the grid power but low power prices for export power to grid. Besides that, by introducing electrolytic H_2 as a controllable load, and by accessing wind power from a weak grid to produce H_2, the wind power integrated into weak grid can be increased especially when generating the stochastic power. Thus, the performance of weak grid connected system can be improved. Total hydrogen generated depends on power access from weak grids. One of the disadvantages of HESS is its limited ability of its electrolyzer to match fluctuating power input [19,42,84].

Since a typical HESS does not consist a perfect characteristic to mitigate the wind fluctuation problems, a critical control strategy is required, as explained in [87,88], while the utilization of fuzzy logic controller for HES application is constructed in [89]. Sander et al., proposed a new concept of variable energy storage in [90] by combining LIQuid Hydrogen (LH2) with SMES, LIQHYSmes. This combination helps to increase operational safety for large stationary energy storage and to balance the load during fluctuation from seconds to a few hours.

Table 2 gives a comparison between the four types of energy storage discussed. Different application category of energy storage means different ability of the energy storage to improve the grid system. Bulk energy storage is designed to smooth the power integrated to the grid. There are only two existing bulk energy storages which are Pump Hydro Storage and CAES and recent analysis regards to CAES.

Power quality is designed to improve the active power received by the grid and the best examples for this application are FESS, SMES system and capacitors due to their fast response rates and ability to charged and discharged frequently. Distributed generation is designed to feed the isolated load when stochastic generator is not sufficient. In addition, the storage capability of CAES system is higher compared to SMES system, FESS and HESS [22,37,84].

5. Conclusion

This paper provides a review on the operating system of four types of energy storage system and their capability to stabilize grid systems in different ways based on their storage characteristics. CAES system acts as a bulk energy storage, which is normally used for large scale energy storage and it gives better performance in providing constant active wind power to grid even at low wind speed compared to SMES system, FESS and HESS. A suitable control system is required to switch on and off the CAES system so that the system will only be operated at low wind speed and high demand.

SMES system and FESS are designed to enhance the quality of active power generated to the grid by absorbing the surplus power during high wind speed and to be used at low wind speed. This charging and discharging processes normally occur at the DC link to match the grid frequency and storage frequency. These storages also require a control system to limit the charging and discharging power at DC link. Surplus power HESS is coupled with stochastic power generation to improve the performance of weak grid system. All these mentioned energy storages have the ability to smooth-out wind power fluctuation during variable wind speed. PMSG gives better performance in dealing with variable wind speed compared to DFIG due to its fast response and high efficiency.

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